

Heavy-flavour production and nuclear modification factor in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV with ALICE

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Abstract

The measurement of heavy-flavour production and nuclear modification factor in heavy-ion collisions provides insights into the mechanisms of parton energy loss in the hot and dense medium formed in these collisions. ALICE results on heavy-flavour decay electrons and muons and on D mesons are presented.

Keywords: Heavy-ion collisions, QGP, Heavy flavour, Nuclear modification factor, ALICE

1. Introduction

Charm and beauty quarks are effective probes of the properties of the hot and dense strongly-interacting medium formed in high-energy nuclear collision, the Quark-Gluon Plasma (QGP). They are sensitive to the transport properties of the medium, since they are predominantly produced on a short time scale in primary partonic scattering processes with large virtuality Q^2 . Due to their large masses ($m_c \sim 1.5$ GeV/ c^2 and $m_b \sim 4.5$ GeV/ c^2) and the minimum virtuality, $Q_{\text{min}}^2 = (2m_Q)^2$, required for the production of a $Q\bar{Q}$ pair, the temporal and spatial scales, $\Delta\tau \sim \Delta r \sim 1/Q$, are sufficiently small for the production to be unaffected by the QGP medium.

For hard processes, in the absence of nuclear and medium effects, a nucleus–nucleus (A–A) or a proton–nucleus (p–A) collision would behave as a superposition of independent nucleon–nucleon (NN) collisions. The charm and beauty differential yields dN/dp_T would scale from pp to A–A or p–A proportionally to the number N_{coll} of inelastic NN collisions (binary scaling). The binary scaling is “broken” by initial-state and final-state effects. In the initial state, the nuclear environment affects the quark and gluon distributions, which are modified in bound nucleons depending on the parton fractional momentum x and the atomic mass number A [1]. Partons can also lose energy in the initial stages of the collision via initial state radiation [2] or experience transverse momentum broadening due to multiple soft collisions before the $Q\bar{Q}$ pair is produced [3]. The final-state effects are related to the heavy-quark interaction with the medium. The most relevant effect is partonic energy loss due to medium-induced gluon radiation (inelastic processes) [4, 5] and collisions with medium constituents (elastic processes) [6]. The modification of binary scaling is quantified via the nuclear modification factor, defined as $R_{\text{AA}}(p_T) = \frac{(dN/dp_T)_{\text{AA}}}{\langle T_{\text{AA}} \rangle (d\sigma/dp_T)_{\text{pp}}}$, where $\langle T_{\text{AA}} \rangle$ is the average nuclear overlap function calculated with the Glauber model in the considered centrality range. Quarks are predicted to lose less energy than gluons due to their smaller colour coupling factor. In addition, the dead-cone effect is expected to reduce small-angle gluon radiation, thus the energy loss, for heavy quarks with respect to light quarks [7, 8]. This effect can be tested by comparing the R_{AA} suppression of the mostly gluon-originated light-flavour hadrons and that of D and B mesons. However, the comparison of heavy-flavour hadron and pion R_{AA} cannot be interpreted directly as

a comparison of charm, beauty and gluon energy losses due to the different fragmentation functions and slope of the p_T -differential cross sections [9, 10].

2. Analysis and results

Charm and beauty production was measured with ALICE [11, 12] in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using electrons and muons from semi-leptonic decays of heavy-flavour hadrons and fully reconstructed D-meson hadronic decays. Electron tracks were identified in the central rapidity region using the specific energy loss in the gas of the Time Projection Chamber (TPC) combined with the information provided by the Time Of Flight (TOF) detector or the electromagnetic calorimeter (EMCAL). The data were collected using minimum bias and EMCAL triggers. Muon tracks were reconstructed in minimum bias trigger events in the Forward Muon Spectrometer ($-4 < \eta < -2.5$). D mesons were reconstructed at mid-rapidity ($|y| < 0.5$) in minimum bias Pb–Pb collisions via their hadronic decay channels: $D^0 \rightarrow K^- \pi^+$ (with branching ratio, BR, of $3.88 \pm 0.05\%$), $D^+ \rightarrow K^- \pi^+ \pi^+$ (BR of $9.13 \pm 0.19\%$), $D^{*+} \rightarrow D^0 \pi^+$ (BR of $67.7 \pm 0.5\%$) and $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$ (BR of $2.28 \pm 0.12\%$) [13] and their charge conjugates. D-meson selection was based on the reconstruction of decay vertices displaced by a few hundred μm from the interaction vertex, exploiting the high track spatial resolution close to the interaction vertex of the collision, granted by the Inner Tracking System detector (ITS). Charged pions and kaons were identified using TPC and TOF signals.

The reference pp cross section of heavy-flavour decay electrons and D mesons at $\sqrt{s_{NN}} = 2.76$ TeV was obtained by a pQCD-based energy scaling of the p_T -differential cross section measured at $\sqrt{s} = 7$ TeV. The scaling factor and its uncertainties were evaluated as explained in [14]. The muon R_{AA} was calculated using the pp cross section measured at $\sqrt{s} = 2.76$ TeV [15].

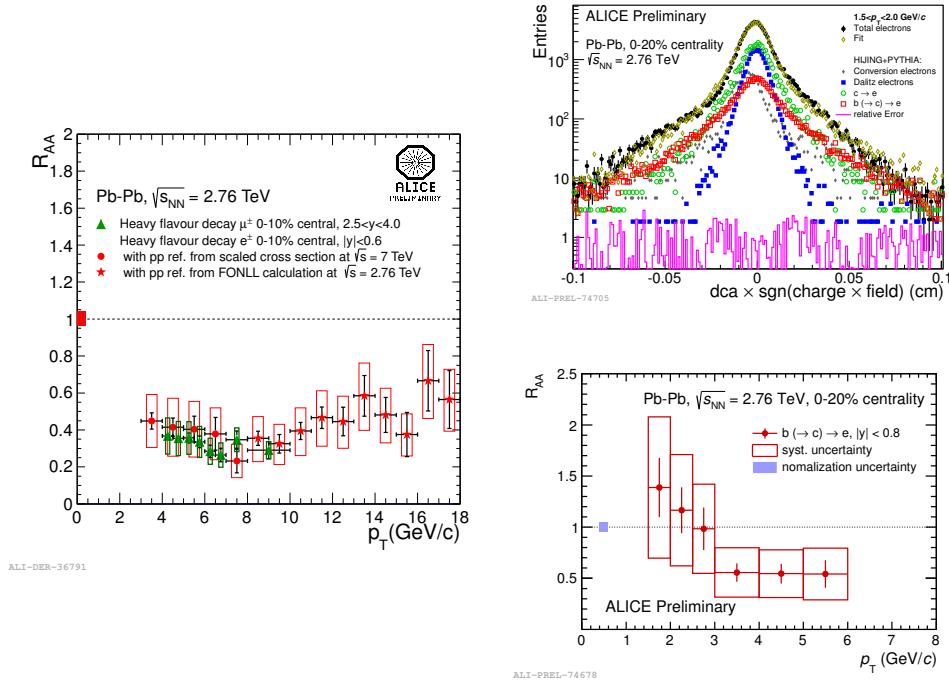


Figure 1: Left: R_{AA} of heavy-flavour decay electrons at central rapidity and heavy-flavour decay muons at forward rapidity in central (0–10%) Pb–Pb collisions, as a function of p_T . Right top: Inclusive electron impact parameter distribution (black points) fitted with templates for the various electron sources obtained from simulations. Right bottom: beauty decay electron R_{AA} as a function of p_T measured in central Pb–Pb collisions.

The left panel of Fig. 1 shows the heavy-flavour decay electron and the heavy-flavour decay muon R_{AA} , measured in the 10% most central Pb–Pb collisions, at central ($|y| < 0.6$) and forward rapidity ($2.5 < y < 4$) respectively. A clear

suppression is observed for both electrons and muons in the measured p_T range and it is compatible within uncertainties at central and forward rapidity. ALICE measured also the nuclear modification factor, R_{pPb} , of heavy-flavour decay electrons and muons in minimum-bias p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and the results are compatible with unity [16], indicating that the suppression observed in central Pb–Pb collisions is due to final state effects. The fraction of electrons produced by beauty-hadron decays was extracted from a fit to the electron impact parameter distribution (right top panel of Fig. 1). The electron sources were included in the fit through templates obtained from simulations. The data indicate that the beauty-decay electron R_{AA} is smaller than unity for $p_T > 3$ GeV/c (right bottom panel of Fig. 1). The same measurement was performed in p–Pb collisions and the compatibility of the resulting R_{pPb} with unity suggests that in Pb–Pb collisions the b quark is affected by the interaction with the hot medium.

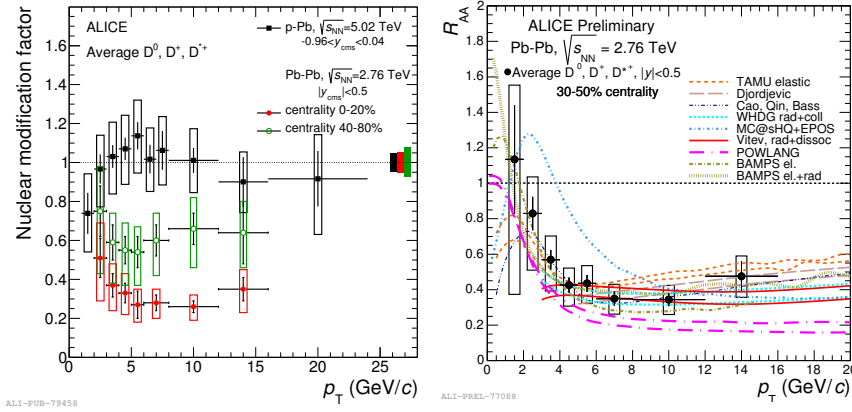


Figure 2: Left: average R_{pPb} of prompt D^0 , D^+ and D^{*+} mesons as a function of p_T compared to the prompt D-meson R_{AA} in the 20% most central Pb–Pb collisions and in the 40–80% centrality class [17]. Right: average prompt D-meson R_{AA} in Pb–Pb collisions in the 30–50% centrality class compared with theoretical models including parton energy loss [9, 19].

In the left panel of Fig. 2 the comparison of the average of prompt D^0 , D^+ and D^{*+} nuclear modification factors measured in two centrality classes of Pb–Pb collisions [17] (0–20% and 40–80%) and in minimum bias p–Pb collisions is presented. The suppression observed in the 20% most central Pb–Pb collisions (about a factor 4 for $p_T > 5$ GeV/c) is predominantly induced by final state effects due to charm quark energy loss in the medium [18]. In the right panel of Fig. 2 the average of prompt D^0 , D^+ and D^{*+} R_{AA} measured in Pb–Pb collisions in the centrality class 30–50% is compared with several theoretical models including in-medium energy loss [9, 19]. A significant suppression is observed also in the 30–50% centrality class for $p > 4$ GeV/c. ALICE measured also the D_s^+ R_{AA} [20], observing a similar suppression to that of D^0 , D^+ and D^{*+} in the p_T interval from 8 to 12 GeV/c. At lower p_T the current uncertainties does not allow to draw a clear conclusion. The comparison of the theoretical predictions with different observables, such as the D-meson production cross section in 30–50%, the R_{AA} in 30–50%, the R_{AA} in 0–7.5% and the azimuthal dependence of the nuclear modification factor in 30–50% centrality class [21], allows to constrain the description of the energy loss mechanisms (see e.g. [21] for a discussion).

The comparison of the centrality dependence of the R_{AA} of D mesons and of J/ψ from B meson decays (measured by CMS [22]) is displayed in the left panel of Fig. 3. The p_T range 8–16 GeV/c was chosen for D mesons in order to have a similar average transverse momentum (about 10 GeV/c) than that of B mesons decaying in a J/ψ in the measured p_T interval of 6.5–30 GeV/c. It shows an indication for a stronger suppression for charm than for beauty at high p_T in central Pb–Pb collisions. The two measurements are described by the predictions based on a pQCD model including mass-dependent radiative and collisional energy loss [9]. In this model the difference in R_{AA} of charm and beauty mesons is mainly due to the mass dependence of the charm and beauty quark energy loss, as shown by the curve in which the non-prompt J/ψ R_{AA} is calculated assuming that b quarks suffer the same energy loss as c quarks. The right panel of Fig. 3 shows the comparison of R_{AA} as a function of centrality of D^0 mesons and charged pions

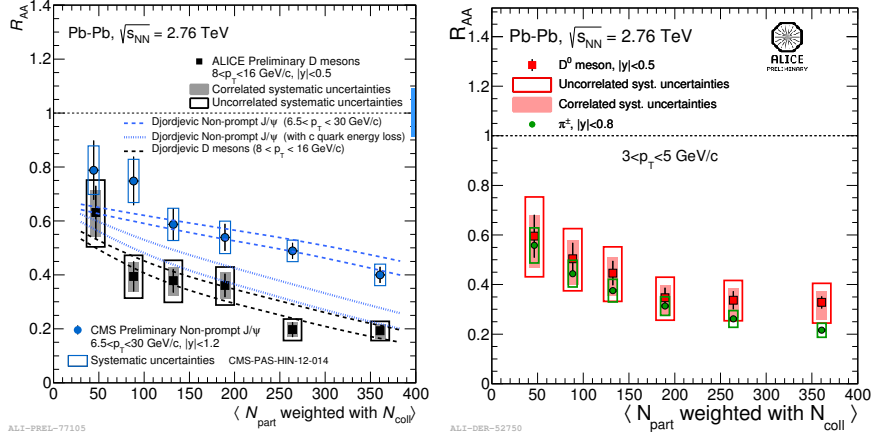


Figure 3: Left: centrality dependence of the R_{AA} of prompt D mesons and of J/ψ from B meson decay (measured by CMS [22]) compared with a pQCD model including mass dependent radiative and collisional energy loss [9]. Right: comparison of D^0 and charged pion R_{AA} as a function of centrality for $3 < p_T < 5$ GeV/c.

for $3 < p_T < 5$ GeV/c. The results are compatible within uncertainties: better precision is needed to investigate the expected difference of gluon and light quark energy loss with respect to charm.

3. Conclusions

The results obtained with ALICE using the data from the LHC Run-1 (2010-2013) indicate a strong suppression of heavy flavour production in central Pb–Pb collisions for $p_T > 3$ GeV/c, observed for heavy-flavour decay electrons and muons, for electrons from beauty decays and for D mesons. From the comparison with p–Pb measurements, it is possible to conclude that the suppression observed in Pb–Pb collisions is mainly due to final state effects, i.e. the interaction of heavy quarks with the hot medium. The comparison of prompt D-meson and non-prompt J/ψ R_{AA} shows an indication of larger suppression for D mesons with respect to B mesons, that can confirm the mass dependent nature of the energy loss mechanisms.

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